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AUTOMATIC SHOCK CALIBRATION OF ACCELEROMETERS

J. F. Schneider
R. J. Nielsen

February 1984

Final Report
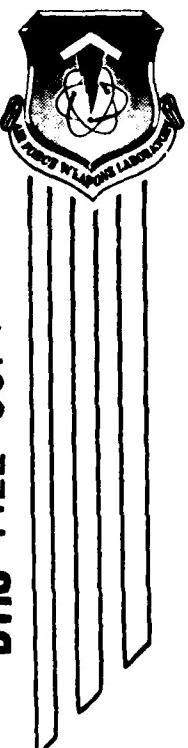
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AIR FORCE WEAPONS LABORATORY
Air Force Systems Command
Kirtland Air Force Base, NM 87117

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This report has been reviewed and is approved for publication.

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19. ABSTRACT (Continue on reverse if necessary and identify by block number)

The shock calibration of accelerometers is automated by feeding both the test signal and the reference signal to a computer. All pertinent parameters are entered in the computer prior to the test. The test program (software) produces a scaled and calibrated plot of the test signal and the inverted reference signal, and prints on the plot and the measured g values, the measured sensitivity of the test accelerometer, and the deviation from the manufacturers' stated sensitivity, in addition to the pertinent test and setup parameters. Successive tests can be averaged to eliminate statistical variations. A hard copy of the results is obtained when desired. Ten times more accelerometers can be calibrated and documented with the described automated procedure than was possible before.

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ILLUSTRATIONS

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I. INTRODUCTION

The previous procedure of accelerometer calibration for shock signals has been rather slow and inaccurate. The g-level measurements of both the test signal and the reference signal were made with a ruler from a 2-3/4 x 3-3/4 Polaroid photograph taken off a regular oscilloscope display in real time. Not more than one inch amplitude was available per signal. The method of calibration was not changed, but the procedure was automated. The oscillo-scope was replaced by an analog-to-digital (A/D) converter, the measurements were evaluated at computer speed, and the Polaroid photograph was replaced by a hard copy of the display on the terminal screen, which also contained the complete test results with all necessary setup and transducer parameters.

II. METHOD

2.1 DROP BALL CALIBRATOR

The principal design of a drop ball calibrator is shown in Figure 1. The ball falling through the tube imparts its acquired momentum on the anvil on which the reference and the test gage are mounted. A damping pad is used to tailor shape and force of the impact while the size of the ball and the anvil determine the range. The anvil is held in place magnetically until the ball hits, producing a haversine-shaped acceleration signal in the transducers. A trigger signal is generated by the interruption of a light beam so that the transducer signals can be captured on a scope or by the computer analog input interface. Figure 2 is a photograph of an implementation of a drop ball calibrator. For a description of the method in manual operation, see Reference 1.

2.2 DATA ACQUISITION

The transducers receive their proper excitation which is constantly monitored on volt and ammeters for exact values. The accelerometer output signals are routed through low-pass filters, which remove unrelated measurement system noise, and then applied to the computer analog input where they are digitized. These filters also condition the signals to comply with the Nyquist sampling requirements (Ref. 2). The sampled data are then processed by the automation program ACCAL. Figure 3 shows the drop ball calibrator setup with signal conditioning and other measurement equipment.

2.3 DATA PROCESSING

Both signals are calibrated with the previously entered scale factors and analog gain factors. An autoscale algorithm sets the display scale so that maximum visibility is obtained. The reference signal is inverted for a more convenient display to avoid interference with the test signal. The apparent test gage sensitivity is calculated from the reference gage measurement and compared to the manufacturer sensitivity data. The percentage difference is evaluated and a bell is rung when a certain value is exceeded.

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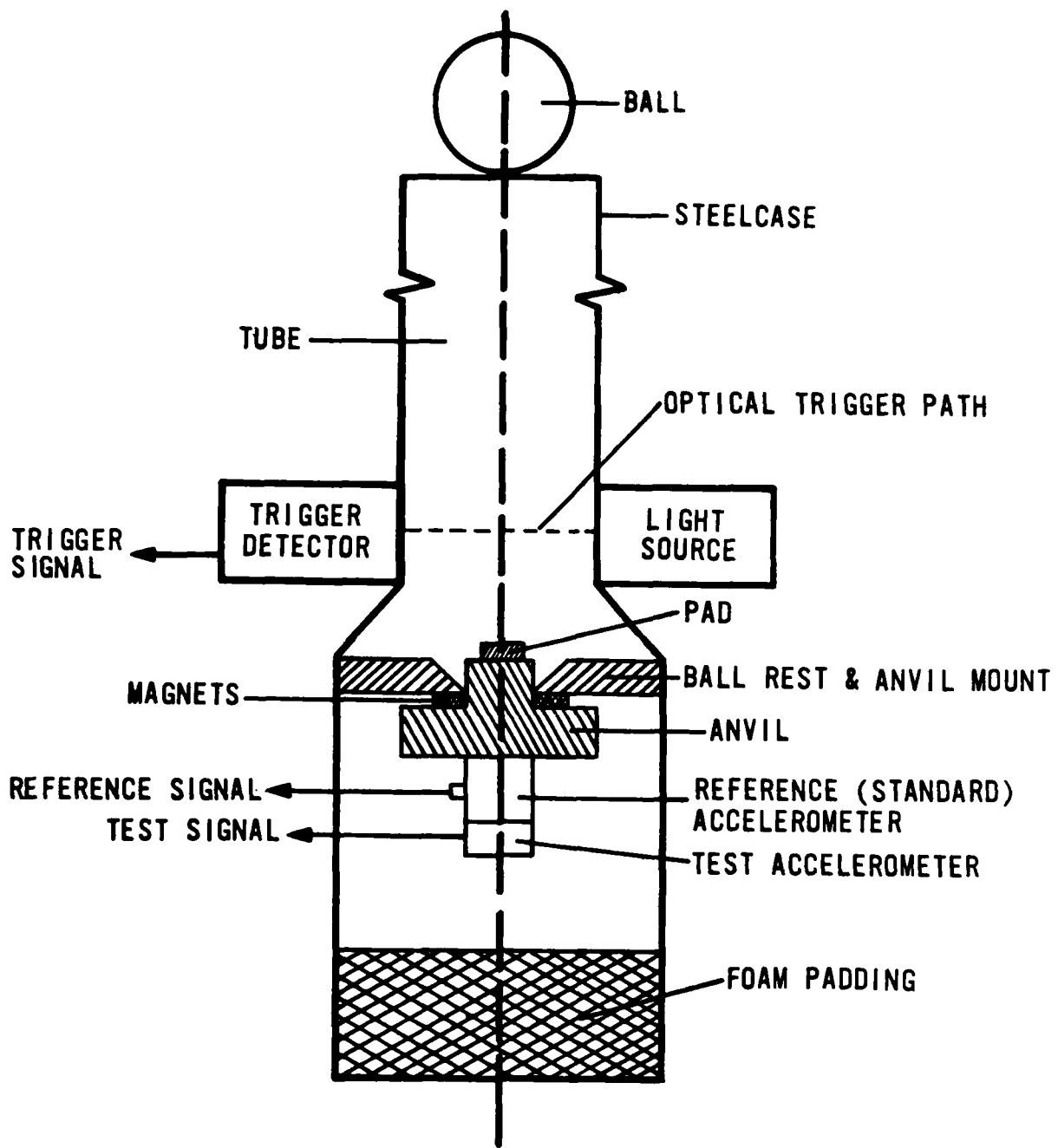
Figure 1. Drop ball calibrator schematic.
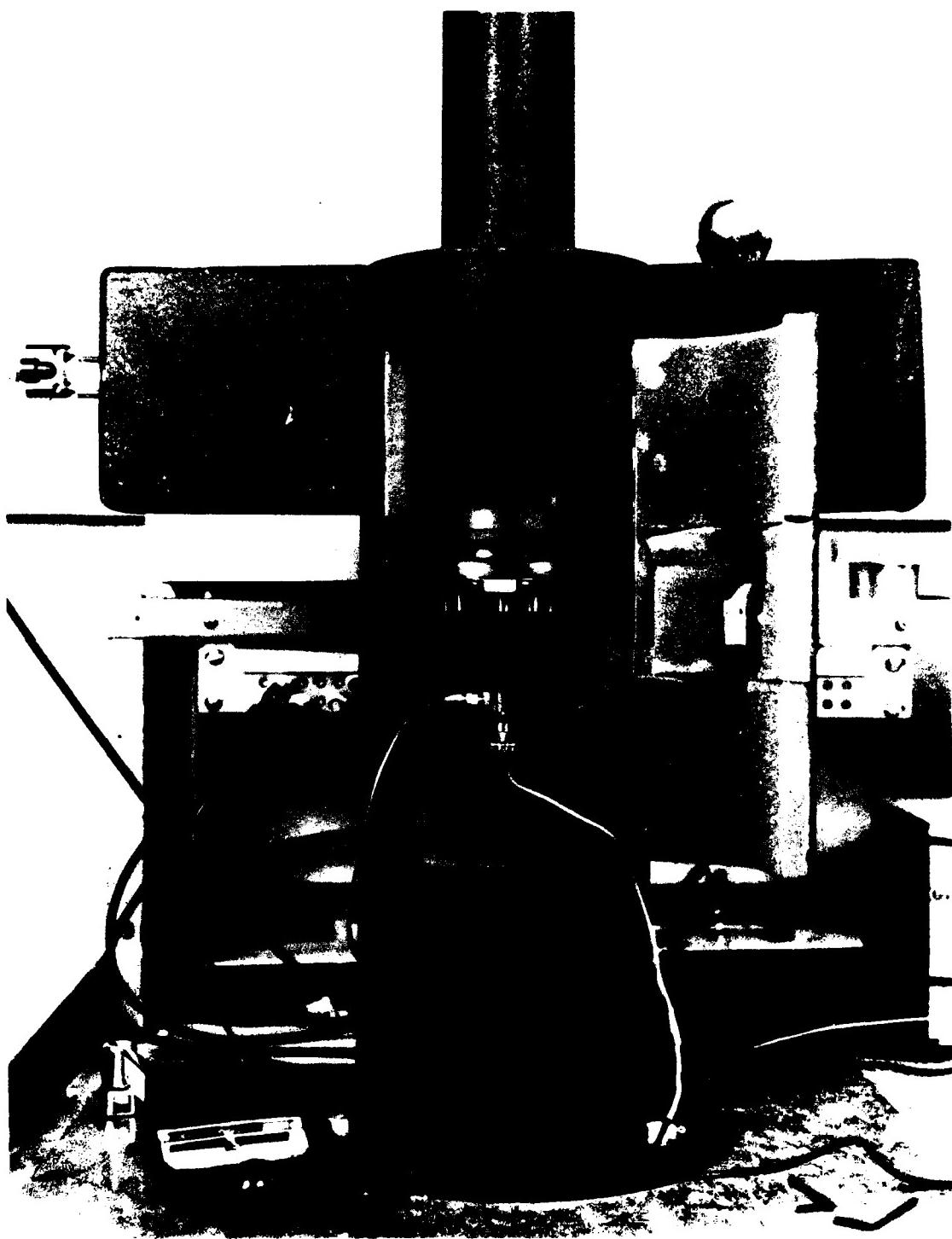
Figure 2. Drop ball calibrator.

Figure 3. Measurement setup.

A major part of the automation consists in having the plot of the two signals include all parameter and measurement information which previously had to be recorded by hand or was not documented at all. A hard copy of this display can be obtained on demand in 10 s and is made a permanent part of the gage documentation.

Several measurements on the same gage under the same conditions can be averaged to reduce the effect of statistical measurement uncertainties. A second, time-base-expanded plot is provided that shows the details of the shape of the returned signals.

In going from one measurement to the next, only those parameters need to be entered that are different from the last setup. Analog signal offsets are removed by a baseline calculation that consists of averaging a large number of data points before the shock signal arrives and correcting the data for this offset. The input range for the analog computer interface is computed from the parameter entries and the input attenuator is automatically set up to an optimum value..

The data processing station, part of which is used for the accelerometer calibration, is shown in Figure 4.
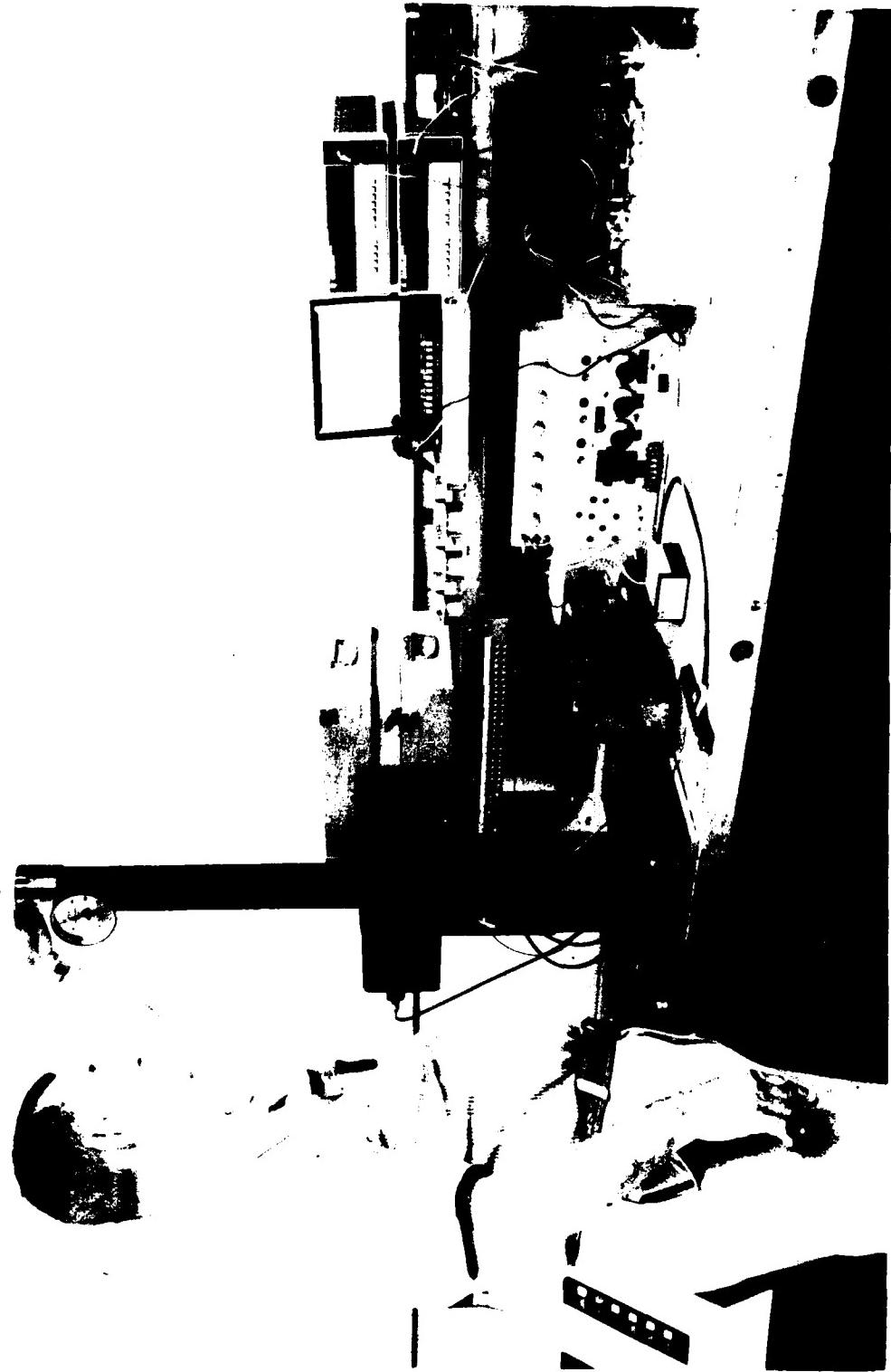
Figure 4.   Data processing station.

III. PROCEDURE

3.1 OVERVIEW

The calibration procedure described here is for piezoresistive accelerom-
eters. It starts with the transducer channel history that is documented on a
form called the Channel History Sheet. The entries which link the transducer
to a particular test and channel and which are particular requirements for
this measurement are provided by the Instrumentation Project Officer (IPO).
The static tests then begin in the calibration laboratory. These are con-
figuration measurements like bridge resistances and calibration step response.

The dynamic test is conducted with the drop ball calibrator and a
PDP-11/34 computer. It uses the Time Series Language (TSL)* operating system
which provides A/D input interfacing and a powerful display package. The hard
copy of the computer graphics output is then attached to the Channel History
Sheet.

3.2 HARDWARE

3.2.1 <u>General Considerations</u>. The Air Force Weapons Laboratory (AFWL)
Form 49 (Transducer Channel History, Sample in Fig. 5) outlines the checks and
inspections performed on each transducer before it is used in an instrumenta-
tion system. Before performing these checks the following should be checked.

a. Cleanliness of work area.

b. Foam pad for gage rest. Used to protect transducer from inadvertent
high-g inputs.

c. Positive electrical connections.

d. Torque wrench capable of applying 3 N·m (26 in-lbf).

e. Drop ball calibrator survey notebook. Allows operator to select anvil
and ball to approximate the dynamic input that he wants for the test gage.

f. Project officer's prediction and assignment sheet.

g. Manufacturer's data card. Used to compare data for final acceptance/
non-acceptance.

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*Trademark of GenRad, Time/Date Division, San Carlos, California.

CHANNEL HISTORY

Field		
IPD 4*	TYPE MEAS 5*	RESPONSE 6*
	RM TEMP 13	CAL F 14
XDUCER RANGE AND S/N 12	EVENT 1*	XDUCFR MFR AND MODEL 7*
	MEAS NO. 2*	VAN/REC/TK/MUX/VCO 3
	P.C. CARD NO. 8	DESIRED CAL VOLTAGE 10*
		9 MV
	MECHANICAL INSPECTION 15	MFGR SENS 17
	ACTUAL CAL EU 16	CALC SENS 18

	LAB	QC	VAN	VAN	VAN	VAN	VAN	VAN (Post Test)
DATE								
IR-CONDUCTORS TO CASE (megger 50v)	19							
IR-CONDUCTORS TO SHD (megger 50v)	20							
IR-SHD TO CASE (megger 50v)	21							
RED-BLACK OHMS	22							
GREEN-WHITE OHMS	23							
RED-GREEN OHMS	24							
GREEN-BLACK OHMS	25							
BLACK-WHITE OHMS	26							
WHITE-RED OHMS	27							
SHIELD - ⌁ OHMS	28							
EXC CURRENT MA	29							
EXC VOLTAGE V	30							
NOISE P - P	31							
CAL VOLTAGE MV	32							
RESIDUAL IMBALANCE (mv / B EXC VOLTAGE)	33							
FUNCTION CHECK DATE	34							
LIMIT RESISTOR	35							
TECHNICIAN INITIALS	36							

SHUNT CAL, RED-GREEN 37
SHUNT CAL, RED-WHITE 38
LAB APPLIED STIMULUS TRANDUCFR OUTPUT
COMMENT (If necessary, continue on reverse) 39

RED +EXC BLACK -
GREEN +SIG (BLACK) WHITE -SIG
BLACK -EXC
GREEN 2

Figure 5. Channel history sheet.

3.2.2 <u>Calibration Equipment</u>. Figure 6 shows a typical test setup with equipment layout and identification to accomplish the various checks. Other pieces of equipment may be substituted to perform the same functions. Care in setting this up properly results in more accurate data. Ensure that all items with a calibration requirement (standards lab) are within date. Preliminary checks consist of resistance measurements and are performed manually. Dynamic checks use the drop ball calibrator and are performed automatically with a PDP 11/34 computer. Operation of the computer will be described in paragraph 3.3.

3.2.3 <u>Transducer Channel History</u> (Fig. 5)

3.2.3.1 <u>Instrumentation Project Office Entries</u>. All spaces marked with an asterisk are normally completed by the Instrumentation Project Officer (IPO) before receipt in the instrumentation laboratory.

3.2.3.2 <u>Operational Performance Entries</u>

    a. Static Tests

        (1) Turn on equipment items and allow 30 min minimum warmup.

        (2) Megohmmeter: set test voltage to 50 V maximum.

        (3) Select accelerometer of proper range and type according to the requirements on channel history sheet. Record serial number (S/N) in block <u>12</u>.

        (4) Remove test accelerometer from its protection box and place a foam pad.

        (5) Perform mechanical inspection. Record in block <u>15</u>.

        (6) Twist conductors together and connect to megohmmeter as shown in Figure 7. Record conductor to case resistance in block <u>19</u>.

        (7) Connect megohmmeter as shown in Figure 7. Record conductor to shield resistance in block <u>20</u>.

        (8) Connect megohmmeter as shown in Figure 7. Record shield to case resistance in block <u>21</u>.

        (9) Connect test accelerometer to terminal strip, carefully matching color to color.
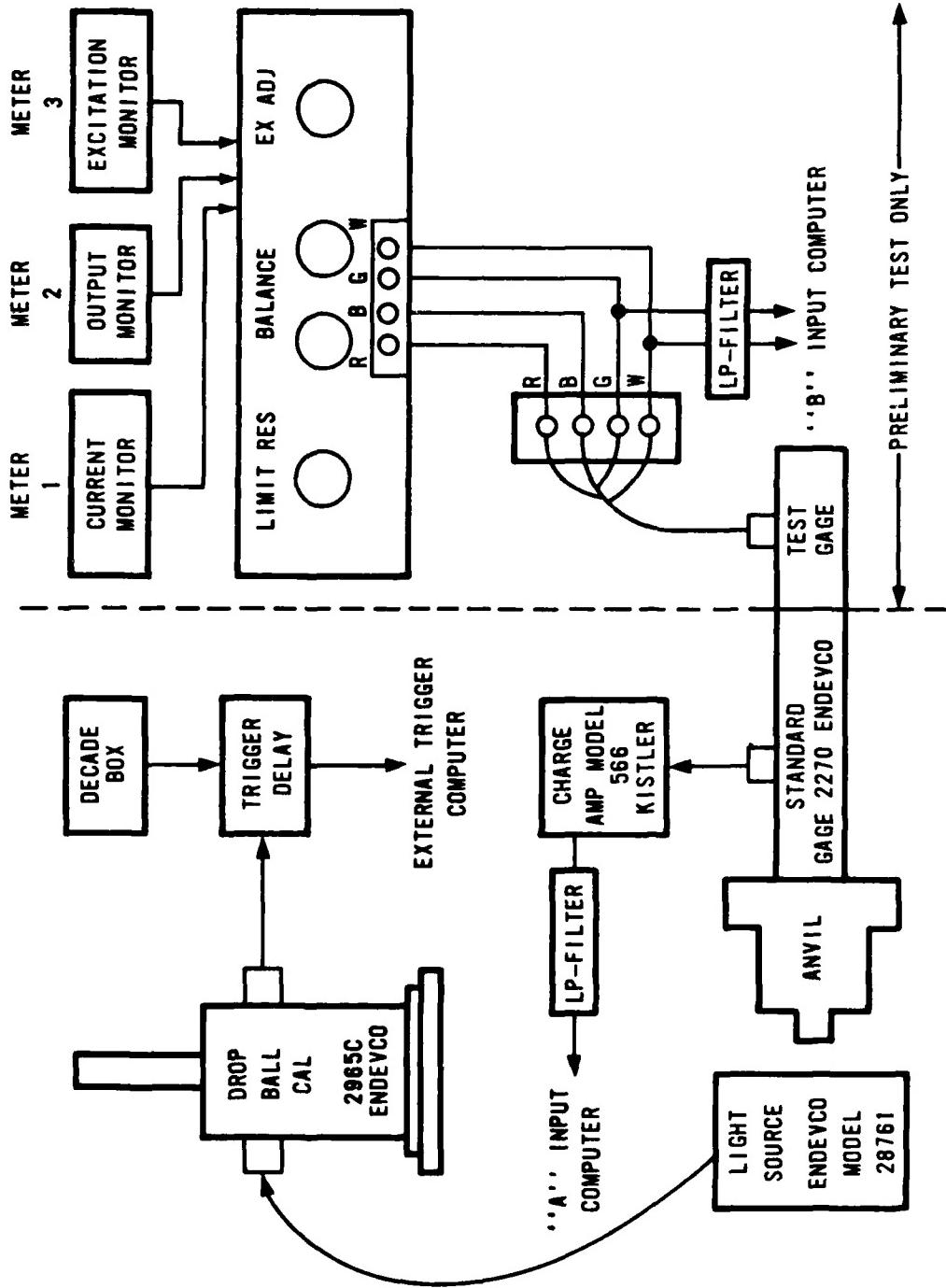
Figure 6. Dynamic test setup.

MEG-OHM METER H/P MODEL 4329A
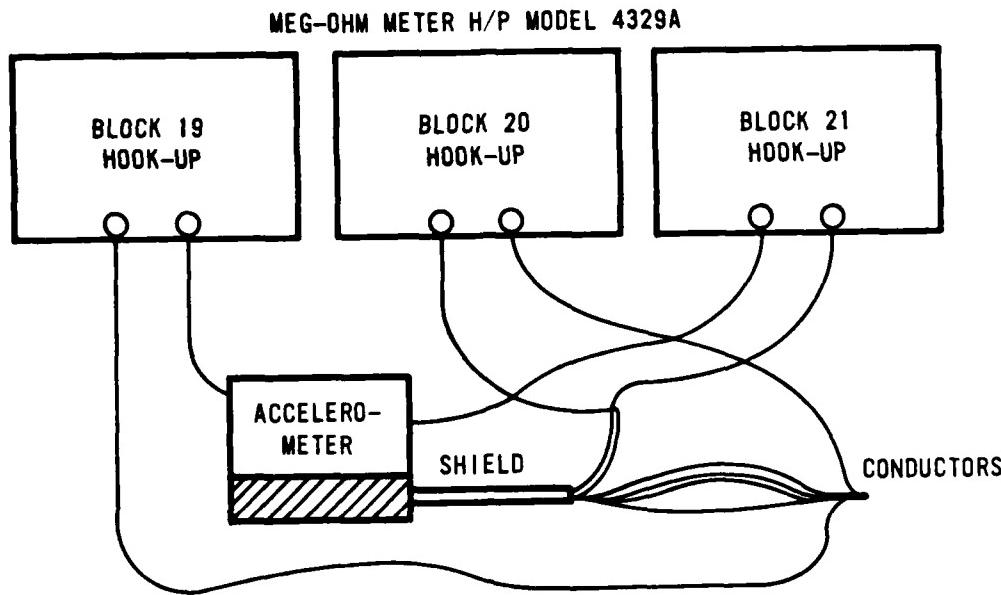
Figure 7. Meter connection.

(10) Select a resistance range on meter No. 2 (output monitor) that allows reading the transducer bridge to the nearest ohm.

(11) Place function switch (Fig. 8) in R_{in} position. Record reading in block 22.

(12) Function switch to R_{out}. Record block 23.

(13) Function switch to R1. Record block 24.

(14) Function switch to R2. Record block 25.

(15) Function switch to R3. Record block 26.

(16) Function switch to R4. Record block 27.

(17) Compare readings obtained in steps (11) and (12) above to R_{in} and R_{out} on manufacturer's data card. Major differences are cause to set transducer aside for additional tests and possible return to manufacturer.

    b. Dynamic Test. Refer to Figure 5 and note that the dynamic hookup includes the standard accelerometer and drop ball calibrator. Caution - Do not hook up transducer until step (7) below is completed.
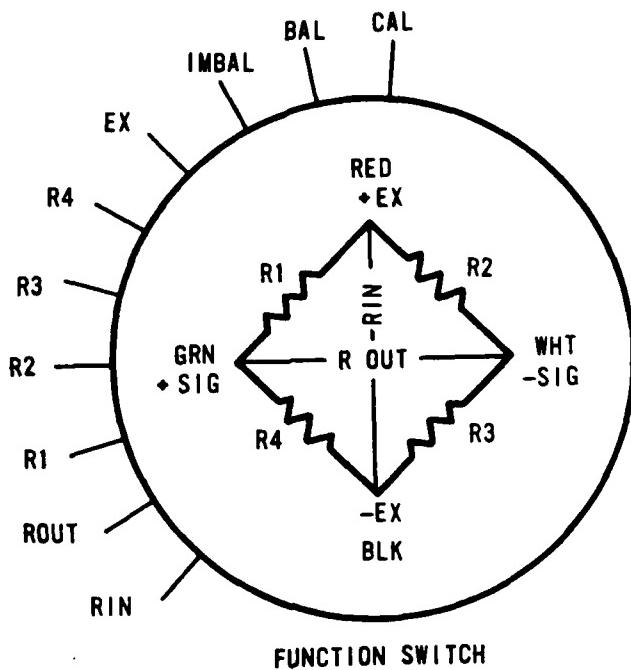
FUNCTION SWITCH

Figure 8. Function switch.

(1) Turn on equipment items and allow 30 min minimum warm up time.

(2) Determine at what acceleration the transducer is to be tested. Generally, if there are a number of transducers of the same range to be tested, select an input that is approximately one-half full-scale and test all gages at this point. This eliminates constant anvil and ball changes. It is also the general level that most IPO's select for the transducer operation because it provides an overrange of 100 percent.

(3) From the drop ball calibrator survey notebook, select an anvil and ball that will effect a g value closest to the test point desired.

(4) Attach standard accelerometer to anvil and torque to 1.5 - 2.8 N · m (13-24 in-lbf).

(5) Attach test accelerometer to standard accelerometer and torque to its specifications.

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(6)   Monitor meter No. 3 and set excitation voltage.

(7)   Turn off power supply.

(8)   Connect transducer to terminal board.

(9)   Turn on power supply and adjust excitation voltage.
Record in block 30.

(10)   Read current monitor, meter No. 1. Record in block 29.

(11)   With function switch in the imbalance position read
transducer residual imbalance and record in block 33.

(12)   Record ambient temperature in block 13.

(13)   Place the anvil so that it is held by the magnets in the
center of the calibrator. The accelerometer cables are routed loosely through
the bottom of the door opening. (A general description of the 2965C Shock
Calibrator is found in para 3.2.5).

(14)   Determine a value of the limit resistor by setting
switch on panel. Generally it is 10K. Record in block 35.

(15)   Select balance pot, normally 20K, and turn until the
output monitor (meter No. 2) reads zero.

(16)   The standard and test transducers are now ready for the
drop test.

(17)   Set up computer as described in paragraph 3.3.

(18)   Reset the charge amplifier offset by pushing button on
front panel.

(19)   Drop the ball down the tube by carefully releasing the
ball with the fingers.

(20)   The computer will now be triggered and indicate on the
monitor whether the trigger delay has been set up properly.

(21)   Determine whether the trigger delay is properly set from
the printout or from the display of the raw plot. Refer to Figure 12: "Put
Peak Here."

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(22) If the transducer signal is not between the arrows on the plot (this condition is also indicated by a printout of the deviations), vary the resistance on decade box and redrop. (If signal needs to be moved to the left, increase resistance; if to the right; decrease.) This is usually a one-time set up, however, operating over a period of time; readjustment may be necessary.

(23) When the above steps have been accomplished, the computer will now take over and furnish a complete calibration history as outlined in paragraph 3.3.

(24) Information to complete blocks 17, 18, 34, 36, 37, and 38 can be transcribed from the computer printout, if so desired.

(25) Determine desired calibration voltage. Use calculated sensitivity, (MV/g) times prediction in engineering units (g). Record in block 9.

(26) All other channel history entries are made by the instrumentation van technicians when the accelerometer measurement channel is set up for a test.

3.2.4 Accelerometer Acceptance. A comparison is made in the computer of the manufacturers sensitivity and the calculated sensitivity from the test drop. A tolerance of ±5 percent has been defined to determine whether the gage is acceptable or not. If a transducer is out of tolerance, try to correct it by retorquing or correcting any obvious errors in hookup. Redrop. If error persists, mark and set aside for additional tests and possible return to manufacturer.

3.2.5 Description of the Model 2965C Shock Calibrator. The ENDEVCO Model 2965C Shock Motion Calibrator is an instrument intended for use in the laboratory to calibrate accelerometers. In addition to performing comparison calibrations, the calibrator is suitable for measuring the resonant frequency of accelerometers.

In the Model 2965C Shock Calibrator, a steel ball is dropped down a tube and impacts an anvil to which the accelerometer is attached. When the impact occurs, the anvil breaks away from a magnetic field and is allowed to fall

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freely until it is caught by cushioning material in the bottom of the calibrator. Just after the shock motion has been applied to the anvil, the ball is stopped by a rubber retaining ring. During the comparison calibration, the same acceleration is applied to both the standard and test accelerometer.

Comparison shock motion calibrations up to 10,000 g are performed with consistent accuracy. The errors in the comparison calibrations are equal to or less than those present in performing absolute calibrations over the same acceleration range. The accuracy of comparison calibration is established by performing an error analysis on all of the instruments used during the calibrations (Ref. 7). This analysis was made possible after tests had demonstrated the amplitude linearity of the accelerometer standard at accelerations up to 50,000 g.

Comparison calibrations can be performed at 20 g, 50 g, 100 g, 500 g, 1000 g, 5000 g, 10,000 g. In addition, calibrations may be performed at intermediate accelerations using smaller balls. The anvils are designed to attach back-to-back an ENDEVCO Model 2270 Standard Reference Accelerometer and a test accelerometer. The standard and test accelerometer outputs are now measured simultaneously in a computer (see paragraph 3.3). The test accelerometer sensitivity is equal to the ratio of the two accelerometer outputs multiplied by the sensitivity of the standard.

3.3 SOFTWARE

3.3.1 Objective. The Drop Ball Calibrator in conjunction with the program ACCAL provides a setup for the automation of the accelerometer calibration procedure. By printing the required information on offset-free, scaled, and calibrated plots, a complete calibration history is provided without the need to write down any additional data.

3.3.2 Operating Instructions

3.3.2.1 Drop Ball Calibrator. Set up Drop Ball Calibrator as described in paragraph 3.2.

3.3.2.2 Starting the Computer

    a. Turn power on.

    b. Insert (1) USER disk or

           (2) ACCAL Floppy disk in respective drive 0.

c. (1) Spin-up disk by pushing RUN. Make sure that Write-Project light is not ON. If it is, push the momentary Write Protect Switch.

(2) Insert floppy disk and close lid.

d. Press the RESET PAGE button on the keyboard to erase the screen of the CRT terminal. V 2.0 will appear on the screen.

e. Boot-up the Computer System by pressing both CTRL and BOOT buttons on the computer console. The BOOT operation will not work if the computer is in RUN status. In this case press CTRL and HLT buttons together to halt the computer before booting.

f. Upon the boot, a line of numbers is displayed on the terminal screen with an 0 symbol on the next line (Fig. 9). Type:

(1) DK with USER disk or

(2) DX with floppy disk

and a Carriage Return (CR). Make sure that the key: TTY LOCK is pushed down. If not, push it down and repeat DK (or DX) and CR.

g. The computer is now in the RT-11 operating system. It signifies this by printing the operating system version number and a dot on the next line (Fig. 10).

Note: When using the floppy disk, it takes several seconds to load the operating system. All subsequent program loads will also take longer than those described for the USER disk.

h. Now the TSL programming system has to be loaded by typing: R TSL. After load (approximately 1 s), the TSL system announces itself on the terminal screen and prints a > on the next line (Fig. 11).

i. The accelerometer calibration program is now to be loaded by typing: LOAD 'ACCAL'. This takes about 10 s. The end of the load is reported by printing a > on the next line (Fig. 12).

3.3.2.3 Inputs from the Calibrator

a. Connect the Standard Gage Signal Conditioner output to the A input of the analyzer through a 10 kHz low-pass filter in pulse mode.

b. Connect the test gage signal conditioner output to the B input of the analyzer through a 10 kHz low-pass filter in pulse mode.

V 2.0

007400 006200 177774 010020
@

Figure 9. Boot display.

V 2.0

007400 006200 177774 010020
@DK
RT-11SJ   V02C-02

.

Figure 10. RT-11 announcement.

V 2.0

007400 006200 177774 010020
@DK
RT-11SJ   V02C-02

.R TSL

TIME/DATA **TSL** V01 31/51
>

Figure 11. TSL announcement.

V 2.0

007400 006200 177774 010020
@DK
RT-11SJ   V02C-02

.R TSL

TIME/DATA **TSL** V01 31/51
>LOAD 'ACCAL'
>

Figure 12. Program loaded.

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3.3.2.4 Running the Program

a. Start the program by typing ACCAL and a CR. The screen will erase and the program announces itself on the screen, followed by requests for entering information (Fig. 13).

b. Each request is printed on the screen, whereupon the program halts and waits for the input. Type in the requested information and finish it with a CR. A complete set of entries is shown in Fig. 14.

c. Corrections of the entry can be made with a RUBOUT key which deletes (internally backspaces) the last character. Then type the correct character. If necessary to go back more than one character, start the entry over (only possible before the CR was typed). Type CTRL U by holding down the CTRL key while typing a U (no CR after that). The computer answers with: DO AGAIN.

d. If more characters are entered than the provided storage can hold, the computer prints: TOO MANY CHARACTERS, and, on the next line: DO AGAIN (Fig. 33).

e. Enough storage is provided for the various entries so that this error seldom occurs.

f. After entering the last information (Range), all entries are displayed for checking, with a request to go ahead or to repeat entries, by asking OK FOR DROP? (Fig. 15):

(1) If O.K. for drop, type Y (yes), and the computer prints: WAITING FOR DROP (Fig. 16). All the answers have to be followed by a CR.

(2) If not O.K., type N (no), and the program advances to a display from which the further course of correcting the previous entries can be selected (fully described below under p.).

(3) If the whole thing is garbled, type R (redo) which brings the program back to the start of the gage parameter entry.

(4) If a complete new start is required e.g., if the test event text entries (Test, Date, and Name) are also wrong, type E (exit) which prints a > on the next line. That means the program has to be called again. Go back to a.

THIS IS THE ACCELEROMETER CALIBRATION PROGRAM

CONNECT REF TO "A" AND TESTGAGE TO "B" INPUT

TEST EVENT IN WHICH GAGE WILL BE USED:

Figure 13.   ACCAL announcement.

THIS IS THE ACCELEROMETER CALIBRATION PROGRAM

CONNECT REF TO "A" AND TESTGAGE TO "B" INPUT

TEST EVENT IN WHICH GAGE WILL BE USED:

EIGHT BALL

DATE: 30 FEB 80
NAME: JACK SPRAT

STD GAGE S/N: UB 34
STD GAGE SENS(MV/G):
? 1.96

TEST GAGE MAKE & MODEL: ENDEVCO 2264A 2KR

TEST GAGE S/N: AR96A
TEST GAGE SENS(MV/G):
? .2492

SELECT RANGE BETWEEN 50 AND 10000 (G)

? 2000

Figure 14.   Entry operation completed.

TEST: EIGHT BALL
DATE: 30 FEB 80   NAME: JACK SPRAT

TEST GAGE: M&M: ENDEVCO 2264A 2KR   S/N: AR96A
          MFR.SENS: .2492(MV/G) PEAK: 0(G)   CAL.SENS: 0.(MV/G)
                                                          DIF: 0%

RANGE: 2000(G), GAIN:.5, ANVIL: 14889.1, BALL: 1.125
STD. GAGE: MFR.SENS: 1.96(MV/G) PEAK: 0(G)   S/N: UB 34

OK FOR DROP(Y OR N),OR REDO ALL(R),OR EXIT(E)?

Figure 15. Listing of entries.

TEST: EIGHT BALL
DATE: 30 FEB 80   NAME: JACK SPRAT

TEST GAGE: M&M: ENDEVCO 2264A 2KR   S/N: AR96A
          MFR.SENS: .2492(MV/G) PEAK: 0(G)   CAL.SENS: 0.(MV/G)
                                                          DIF: 0%

RANGE: 2000(G), GAIN:.5, ANVIL: 14889.1, BALL: 1.125
STD. GAGE: MFR.SENS: 1.96(MV/G) PEAK: 0(G)   S/N: UB 34

OK FOR DROP(Y OR N),OR REDO ALL(R),OR EXIT(E)? Y

WAITING FOR DROP

Figure 16. Request for drop.

g. When the trigger from the calibrator arrives, I AM WORKING AS FAST AS I CAN is displayed in the middle of the screen as shown in Fig. 17. From there it takes 10 s for the first plot (long plot) to appear. A sample of this plot is shown in Fig. 18.

h. A double tone announces that the plot is displayed and that the test gage is within ±5 percent of the manufacturer's sensitivity. A quadruple tone is heard when the test gage is exceeding this tolerance. In this case, try again to correct a possible bad drop. If error persists, mark and set aside the test gage. A set of options to proceed is displayed on the bottom line.

i. For an immediate repeat of the drop, type R followed by CR. The program loops back to the question: OK FOR DROP? Reset the drop ball calibrator and then hit Y. Typing Y before resetting the calibrator makes the program accept any false trigger that might result from reaching in to reset the calibrator.

j. If a plot discrepancy indicates a need to change entries, type S to advance the program to the selection of further action (describe below in p.).

k. If not satisfied, type E and exit the program.

l. If the plot shows that the drop was good enough to be used for averaging, type A to add this plot to the average. This can be done as often as desired. Each plot is annotated with the number of averages done so far. The curves plotted and the parameters printed are the ones of the most recent drop.

m. To advance normally, type C, followed by CR. The next plot (short plot) will appear in 2 s. A sample plot is shown in Fig. 19. One more option is available for continuation. Typing P displays the long plot again, if, e.g., one wants to check it again before committing this drop to the average.

n. To close out the averaging, type X. The last plot is included in the average which is than calculated. A new set of plots (one long and one short) is displayed with a list of the average values. The data

22

TEST: EIGHT BALL
DATE: 30 FEB 80   NAME: JACK SPRAT

TEST GAGE: M&M: ENDEVCO 2264A 2KR   S/N: AR96A
          MFR.SENS: .2492(MV/G)   PEAK: 0(G)   CAL.SENS: 0.(MV/G)
                                                    DIF: 0%

RANGE: 2000(G), GAIN:.5, ANVIL: 14889.1, BALL: 1.125
STD. GAGE: MFR.SENS: 1.96(MV/G)   PEAK: 0(G)   S/N: UB 34

OK FOR DROP(Y OR N),OR REDO ALL(R),OR EXIT(E)? Y

WAITING FOR DROP

I AM WORKING, AS FAST AS I CAN

Figure 17. Display after arrival of trigger.

Figure 18. Long plot, raw.

ACCELEROMETER CALIBRATION (BW= 10 KHZ)

```
2500. ┌─────┬─────┬─────┬─────┬─────┬─────┬─────┬─────┬TEST─┬GAGE─┐
      │     │     │     │     │     │     │     │     │     │     │
      ├─────┼─────┼─────┼─────┼─────┼─────┼─────┼─────┼─────┼─────┤
      │     │     │     │     │     │     │     │     │     │     │
 G    ├─────┼─────┼─────┼─────┼─────┼─────┼─────┼─────┼─────┼─────┤
      │     │     │     │     │     │     │     │     │     │     │
      ├─────┼─────┼─────┼─────┼─────┼─────┼─────┼─────┼─────┼─────┤
PLOT #1│     │     │     │     │     │     │     │     │     │     │
PLOT VALUES ┼─────┼─────┼─────┼─────┼─────┼─────┼─────┼─────┼─────┤
      │     │     │     │     │     │     │     │     │     │     │
DEMONSTRATION┼────┼─────┼─────┼─────┼─────┼─────┼─────┼─────┼─────┤
FOR MANUAL │     │     │     │     │     │     │     │     │     │
      ├─────┼─────┼─────┼─────┼─────┼─────┼─────┼─────┼─────┼─────┤
4 JUN 80│    │     │     │     │     │     │     │     │     │     │
SCHNEIDER┼────┼─────┼─────┼─────┼─────┼─────┼─────┼─────┼─────┤
      │     │     │     │     │     │     │     │     │     │     │
      ├─────┼─────┼─────┼─────┼─────┼─────┼─────┼─────┼─────┼─────┤
      │     │     │     │     │     │     │     │     │     │     │
-2500.└─────┴─────┴─────┴─────┴─────┴─────┴─────┴STD─GAGE(INV)─┘
      .0015                    TIME                      .0035
```

TEST GAGE: M&M: ENDEVCO 2264A 2KG   S/N: AX 03 A
        MFR.SENS: .2918(MV/G) PEAK: 1378(G) CAL.SENS: .2849(MV/G)
                                                DIF: 2%
RANGE: 2000(G), GAIN:.5, ANVIL: 14889.1, BALL: 1.125
STD. GAGE: MFR.SENS: 1.96(MV/G)   PEAK: 1412(G)   S/N: UB 34
CONT(C),REP(R),SWITCH(S),EXIT(E),AVG(A),LAST AVG(AC),PREV.PLOT(P):
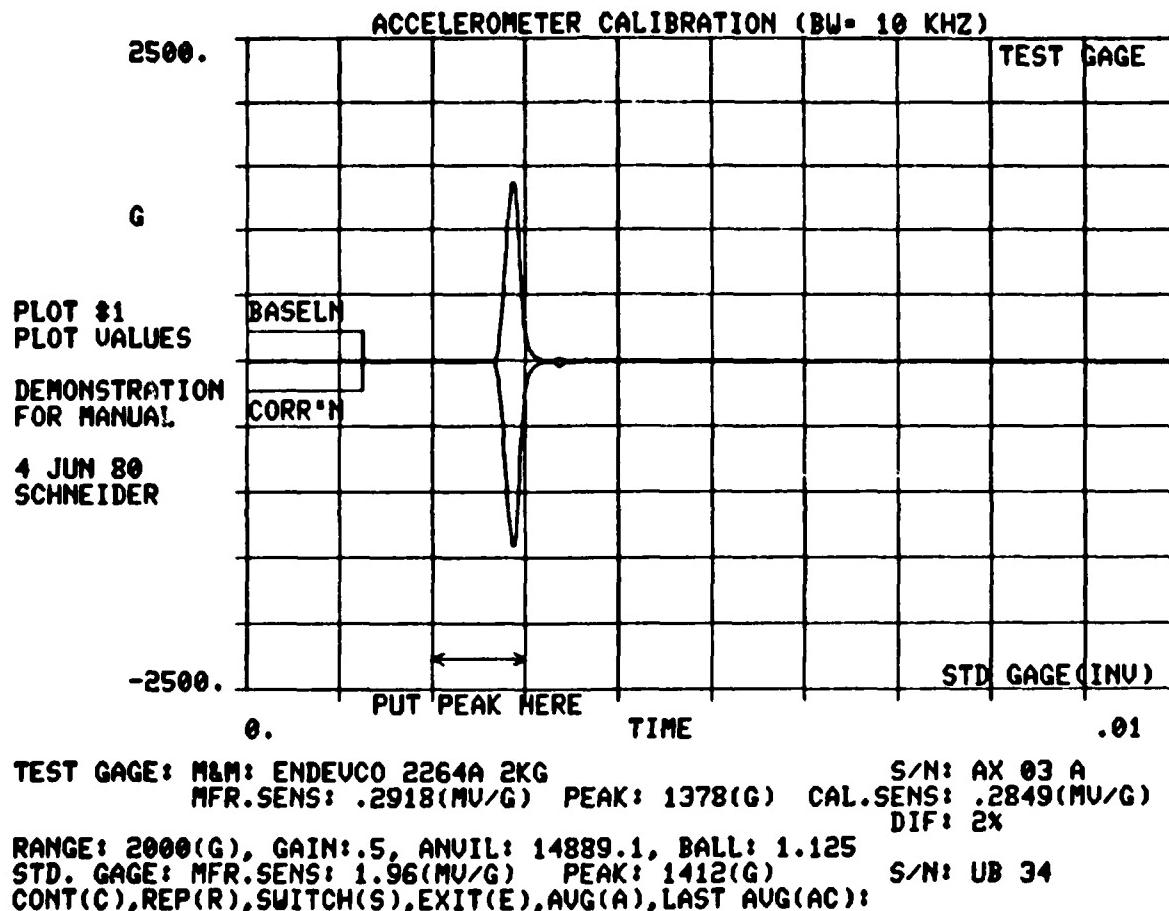
Figure 19.   Short plot, raw.

of this plot are from the last drop, however, (as indicated by the plot number), because the average is taken of the peak amplitudes only. Both plots (without the option listing at the bottom) are automatically copied (Figs. 20 and 21).

o. It is not necessary to call for the short plot, if the long plot is already satisfactory. When no averaging is intended, i.e., only one drop is wanted, AC still has to be used to make copies. In this case the average consists of one drop only. The normal continuation after copies have been made is automatic and winds up with the display for selecting further action.

p. To select further action, a set of options is displayed (Fig. 22) that can be entered into by typing (always followed by CR):

(1) R for immediate repeat, starting at the same place as the other repeats described earlier (i.e., OK FOR DROP?);

(2) L for listing the entire set of entries, winding up with the question: OK FOR DROP?;

(3) G to enter a new range;

(4) M to enter a new Model of a test gage;

(5) N to enter the new S/N for the next test gage of the same model;

(6) B for changing the size of the drop ball, mainly for documentation in the plot legend (see Fig. 23 for the respective screen display);

(7) T for changing the TEST EVENT text only;

(8) E for exit from the program. The screen is erased and a > is printed in the left upper corner;

(9) AC for repeating the automatic plots with the averaged values, if, e.g., the paper in the hard copier had run out.

q. The program can be restarted after an exit or a TSL error with the option of skipping part or all of the entries, if one is sure they are all right:

ACCELEROMETER CALIBRATION (BW= 10 KHZ)
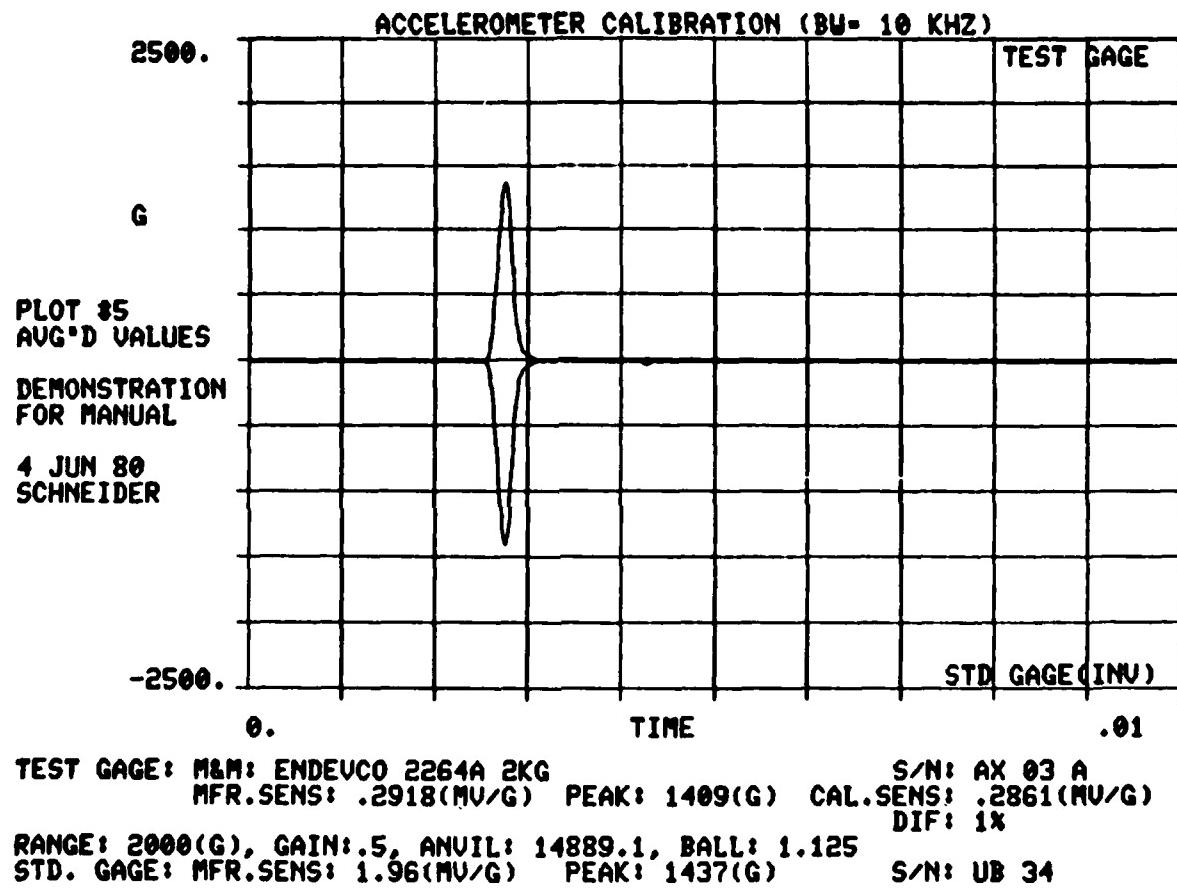
Figure 20.   Long plot, averaged.

ACCELEROMETER CALIBRATION (BW= 10 KHZ)

PLOT #5
AUG'D VALUES

DEMONSTRATION
FOR MANUAL

4 JUN 80
SCHNEIDER

TEST GAGE: M&M: ENDEVCO 2264A 2KG   S/N: AX 03 A
          MFR.SENS: .2918(MV/G) PEAK: 1409(G) CAL.SENS: .2861(MV/G)
                                                         DIF: 1%
RANGE: 2000(G), GAIN:.5, ANVIL: 14889.1, BALL: 1.125
STD. GAGE: MFR.SENS: 1.96(MV/G)   PEAK: 1437(G)   S/N: UB 34
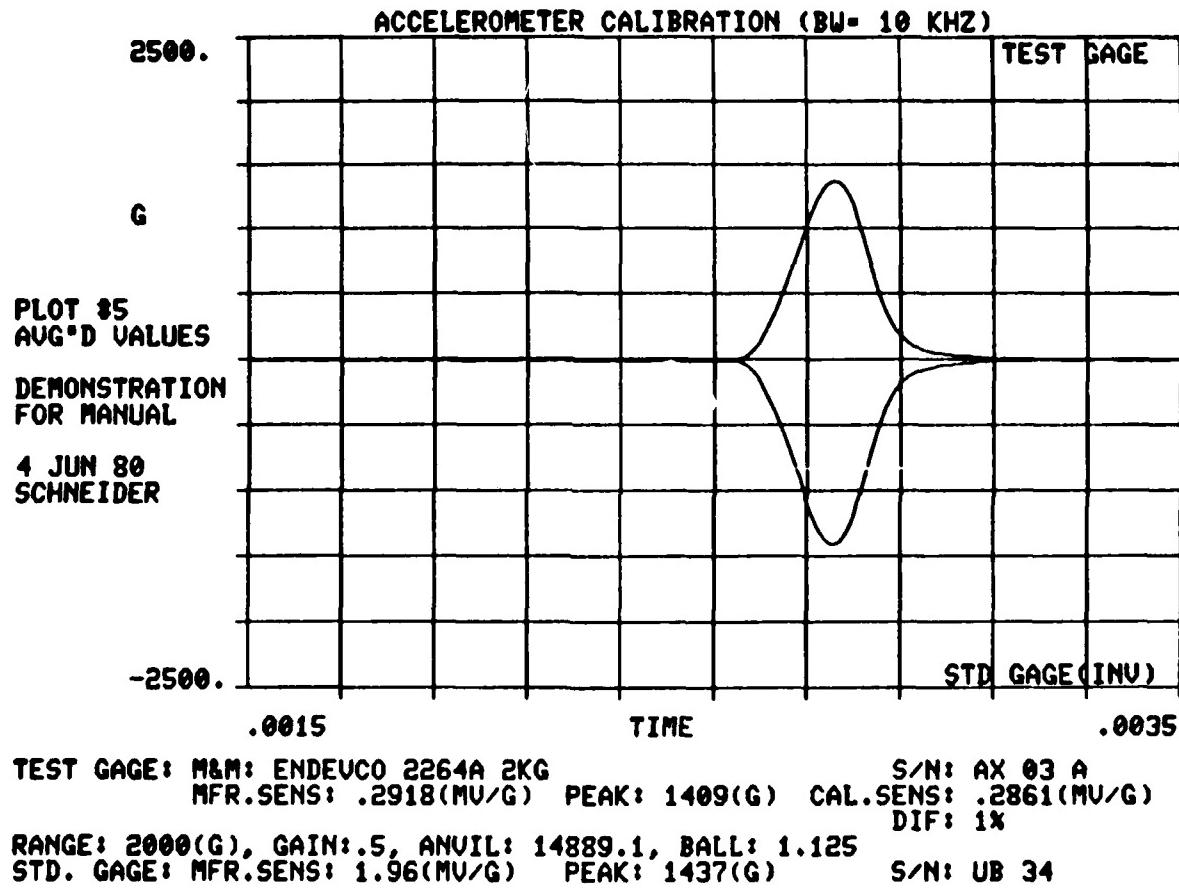
Figure 21. Short plot, averaged.

```
                    SELECT NEXT OPERATION:

                    REPEAT AS IS...R

                    REP AVG PLOTS..AC

                    LIST..........L

                    NEW RANGE......G

                    NEW MODEL......M

                    NEXT GAGE......N

                    EXIT..........E

                    CHANGE BALL FROM 1.125  ...B

                    CHANGE TEST EVENT ONLY ......T

                    TYPE CODE:
```

Figure 22.   Switch options.

```
SELECT NEXT OPERATION:

REPEAT AS IS...R

REP AVG PLOTS..AC

LIST..........L

NEW RANGE......G

NEW MODEL......M

NEXT GAGE......N

EXIT..........E

CHANGE BALL FROM 1.125  ...B

CHANGE TEST EVENT ONLY ......T

TYPE CODE: B

SELECT NEW SIZE FROM:
1.125, 1.25, 1.375, 1.5, 1.625, 1.75. 1.875, 2
?
```

Figure 23.   Request for ball change.

(1) Type ACCAL 0 to go right into the question: OK FOR DROP? If the answer is Y, but the setup is not OK because nothing had been entered yet, the computer answers the Y with: NOT TRUE! and backs up to the beginning of the entries (Fig. 27).

(2) Type ACCAL 1 when a new setup is necessary; but the Test Event, Date, and Name information are already in the program and need not be changed.

3.3.2.5 Notes and Errors

a. All entries and option selections have to be followed by CR. The program will not advance otherwise.

b. If a wrong character is typed in an answer to a question on selecting an option, the question is repeated if there is enough space on the screen.

c. If there is not enough space, as, e.g., at the bottom of the plot, and an incorrect character is typed there, the program does nothing and waits for a correct reply. Every reply, however, needs a CR to become effective and the CRT screen can become full before proper reply is typed. In this case a red light goes on above the keyboard and the program is stopped. No further replies are accepted by the computer. Erase the screen, and type the proper reply after another CR (to close out any false replies that might still be in effect).

d. The parameter and text entries are not altered in the course of the program unless requested by the operator. Therefore, if nothing changes, the program can be called with ACCAL 0 or 1 to shorten the initialization (para 3.3.2.4.q).

e. A wrong range entry (outside displayed limits) is flagged by a tone and the display of the message: WRONG ENTRY, TRY AGAIN (Fig. 29). Enter the proper range and the program will proceed normally.

f. The attenuator settings of the analog input are calculated in the program by using the entered range and gage sensitivities. The attenuators are then set at the next higher full-scale value above the expected

signal amplitude. If the setting requested is beyond the limit of the input hardware, an error message says: OUTPUT (of respective gage) TOO HIGH (Fig. 31) and the program suggests what can be done about it. Typing an

(1) S causes the program to ask the operator to enter a new sensitivity of the gage in question (mostly a case of wrong entries the first time around);

(2) R causes a request to change the g range;

(3) C causes the program to step back for a completely new setup.

g. A change of range can become necessary, e.g., with a high sensitivity gage of 1 mV/g and a 10,000-g range prediction, which amounts to 10 V expected gage output. This is at the limit of the hardware. Therefore, selecting a 9000-g range prediction, for example, can bring the expected gage output down to 9 V.

h. Sometimes the expected gage output is at the very edge of an attenuator setting. This situation can produce an input overload when the gage gets slightly more than the predicted g load. In this case the predicted range is to be increased.

i. The input overload produces a TSL error displayed as a number (in this case 167), the meaning of which can be found in the back of the TSL reference handbook (Ref. 3). In addition, the location in the program where the error occurred is printed (meaningless for the operator), and the program is automatically exited by providing a > on the next line.

j. Recovery from the input overload error is by typing ACCAL 0 (para 3.3.2.4.q), when another try is attempted. The averaging counter is not reset in this case. If a selective change in the entries (e.g., range) is desired when an overload persists, type N after ACCAL 0 as a reply to the question: OK FOR DROP? which steps the program to the selection of further action. (Usually selecting a higher range will remedy a persisting overload, but also check input signals for noise spikes or excessive offset. The latter happens easily when the charge amplifier of the standard gage is not reset before each drop.)

k. Other TSL errors are not expected to occur in normal operation. When one does, recovery is achieved by recalling ACCAL in full or with one of its short versions (para 3.3.2.4.q.).

l. If an M-TRAP xxxxx? error (mouse trap) occurs, something bad has happened, the TSL programming system is not active anymore, and a dot is printed on the next line. Go back to paragraph 3.3.2.2.h., reload TSL and start from scratch.

m. If one gets blocked in the middle of the (ACCAL) program, an emergency exit is available by typing CTRL C, i,e., holding down the CTRL key and typing a C (no CR after that). Sometimes two CTRL C's are needed. This throws the TSL system temporarily out by producing a dot on the next line. But TSL can be restarted by typing RE followed by CR. Start from paragraph 3.3.2.4.a. If ? ILLEGAL COMMAND ? should appear, go back to paragraph 3.3.2.2.h. and start from scratch.

n. A TSL error 130 may occur, when the text information is not in the proper location in the text storage, and the program is requested to print the text. Go back to paragraph 3.3.2.4.a. This situation, however, is directly covered by ACCAL error messages (Figs. 25 and 26) in normal circumstances.

3.3.2.6 Getting Off

a. Flip the disk control switch from RUN to LOAD. Wait approximately 2 min for the disk to despin.

b. After the LOAD-light has appeared, remove disk and close lid again.

c. Turn computer off.

d. Note: Do not leave the disk in the drive; it cannot be removed when the computer is turned off. Similarly, a disk cannot be loaded unless the computer is turned on.

e. When the floppy disk is used, open lid, remove disk and close lid again.

3.3.3 Description of Program

3.3.3.1 Assembly

a. The subroutines of the program are all individually recorded on disk. Their respective file names are the names used in the program with an "N" appended to the name if the name is not longer than five characters. In six-character names, the last character is replaced by an N to produce the file name (see Table 1 for complete list of subroutines).

b. All file name extensions are TSL, e.g., RANGEN.TSL.

c. Group B (which is in binary format) is assembled into file PACBEN.TSL, while group A (which is in ASCII format) is assembled into file ACCALK.TSL. Both groups are listed in Table 1.

TABLE 1. SUBROUTINE LIST

Subroutine Program Name	Disk File Name
Group A: ACCALK.TSL	
ACCAL	ACCALN
BASEL	BASELN
BELET	BELETN
BELLER	BELLEN
CALCUL	CALCUN
COPY	COPYN
DELAY	DELAYN
ENPAR	ENPARN
GCAL	GCALN
INPMAX	INPMAN
LABL	LABLN
LABLC	LABLCN
LISTAL	LISTAN
LISTEX	LISTEN
NAMIN	NAMINN
NAMOUT	NAMOUN
PEAK	PEAKN
RANGE	RANGEN
SCAFAC	SCAFAN
SWITCH	SWITCN
Group B: PACBIN.TSL	
ACE2CH	ACE2CN
DISNEW	DISNEN

d. The final program ACCAL is then assembled by combining PACBIN and ACCALK into file ACCAL.TSL, with an "end" statement appended by adding the file ENDE.TSL.

3.3.3.2 Register Designation

a. Table 2 shows the fixed I-Register designation. The remainder of the registers are used for variable purposes. I6 is used in an extension of the program that is not discussed here.

TABLE 2. I-REGISTER DESIGNATION

I15: Sample Rate Code
I14: Input Attenuator Code
I13: Bandwidth in kHz, Standard Gage
I12: Range in G, Standard Gage
I11: Test Gage, Range in G
I10: Calibration Difference in %
 I9: Block Size
 I8: Average Counter
 I7: Average Close-Out Flag
 I6: XYZ Mode
 I5: Test Gage, Bandwidth in kHz

b. Table 3 shows the fixed R-Register designation. R0 and R2 are used for variable purposes.

TABLE 3. R-REGISTER DESIGNATION

R15: Anvil Number
R14: Ball Size in Inch
R13: Short Plot Maximum Time in Seconds
R12: Full-Scale G Value for Display
R11: Standard Gage Sensitivity in mV/G
R10: Short Plot Minimum Time in Seconds
 R9: Test Gage Sensitivity by Manufacturer in mV/G
 R8: Peak Standard Gage Output in G
 R7: Peak Test Gage Output in G
 R6: Calculated Sensitivity of Test Gage in mV/G
 R5: Full-Scale Time for Long Plot in Seconds
 R4: Peak Standard Gage Output Average Summer
 R3: Peak Test Gage Output Average Summer

c. The fixed registers keep their designation throughout the whole program.

d. Table 4 is a map of locations of entries in the text block. All ASCII character entries are stored there. The number of characters allowed for an entry is generally one less than the size of the storage provided, to leave room for a CR at the end. The test designation entry size is two less than the size of the storage because in the display on the plot, this text is broken up into two lines of 13 and 14 characters each. For the 14th character on the first line, a hyphen is inserted if the entry is larger than 14 characters.

TABLE 4. TEXT BLOCK ORGANIZATION

Block B15: Total Size = 120 Elements

Text	Start No.	No. of Char's	Size
Test Event	0	27	30
Date	30	14	15
Name	45	14	15
Std. Gage S/N	60	14	15
Test Gage M & M	75	29	30
Test Gage S/N	105	14	15

3.3.3.3 Program Boundaries

a. The basic range of setup requirements is determined by the g-ranges to be tested on the drop ball calibrator. These may lie between 50 and 10,000 g. The display times (windows) are determined by the requirement to provide enough time to establish that the gage output has returned to zero, or has suffered a permanent offset in the test (long plot). In order to evaluate the correspondence of test and standard gage signal shape, a close is provided (short plot). The range of these and all parameter values can be found in Table 5.

b. Blocksize and window determine sample rate and achievable bandwidth. Anvil and ball size are values that provide, for the gages tested, the desired g-range. The baseline correction time is used to establish a zero baseline from the analog (usually offset) signal. During this time, no data signal should be present.

TABLE 5. BASIC PARAMETERS

Range (G)	50	250	1000	2500	5000	10,000
Window (ms)	20	20	10	10	10	10
Short Plot Coverage (ms)	3-7	3-7	1.5-3.5	1.5-3.5	1.5-3.5	1.5-3.5
Bandwidth (kHz)	25	25	50	50	50	50
Sample Rate (kS/s)	51.2	51.2	102.4	102.4	102.4	102.4
Sample Rate Code	7	7	10	10	10	10
Base Line Corr (ms)	2.5	2.5	1.25	1.25	1.25	1.25
Block Size	1024	1024	1024	1024	1024	1024
Anvil	14886	14887	14887	14889.1	14889.1	14889.2
Ball Size (inch)	1-1/8	1-1/8	1-1/2	1-1/8	1-1/8	1-1/2

c. As many drops as wanted can be added to the average. As many drops as are necessary can be done before the data are added to the average. The average counter advances only when A has been typed.

3.3.3.4 Program Logic

3.3.3.4.1 Main Program ACCAL (Fig. 24)

a. The first decision is made on the argument of the call. If there is no argument, the program announces itself, goes to the text and parameter entering sequence, and then prints out the whole set of entries.

b. If there is an argument, i.e., the operator wants to skip all or part of the entering sequence, a decision is made on whether the text block is already established (it would not be, if, e.g., an argument would be used on the first call). If the answer is no, an error message is printed (ERR1, Fig. 25) and the program loops back to the beginning of the entering sequence.

c. If the text block is established, a further decision is made on whether there is information in it. If nothing had been entered yet, the same error message is printed (Fig. 25) and the program loops back to the beginning of the entering sequence.

d. If information is found, the type of argument has to be examined. A 1 makes the program skip the text entering by starting at the parameter entry.

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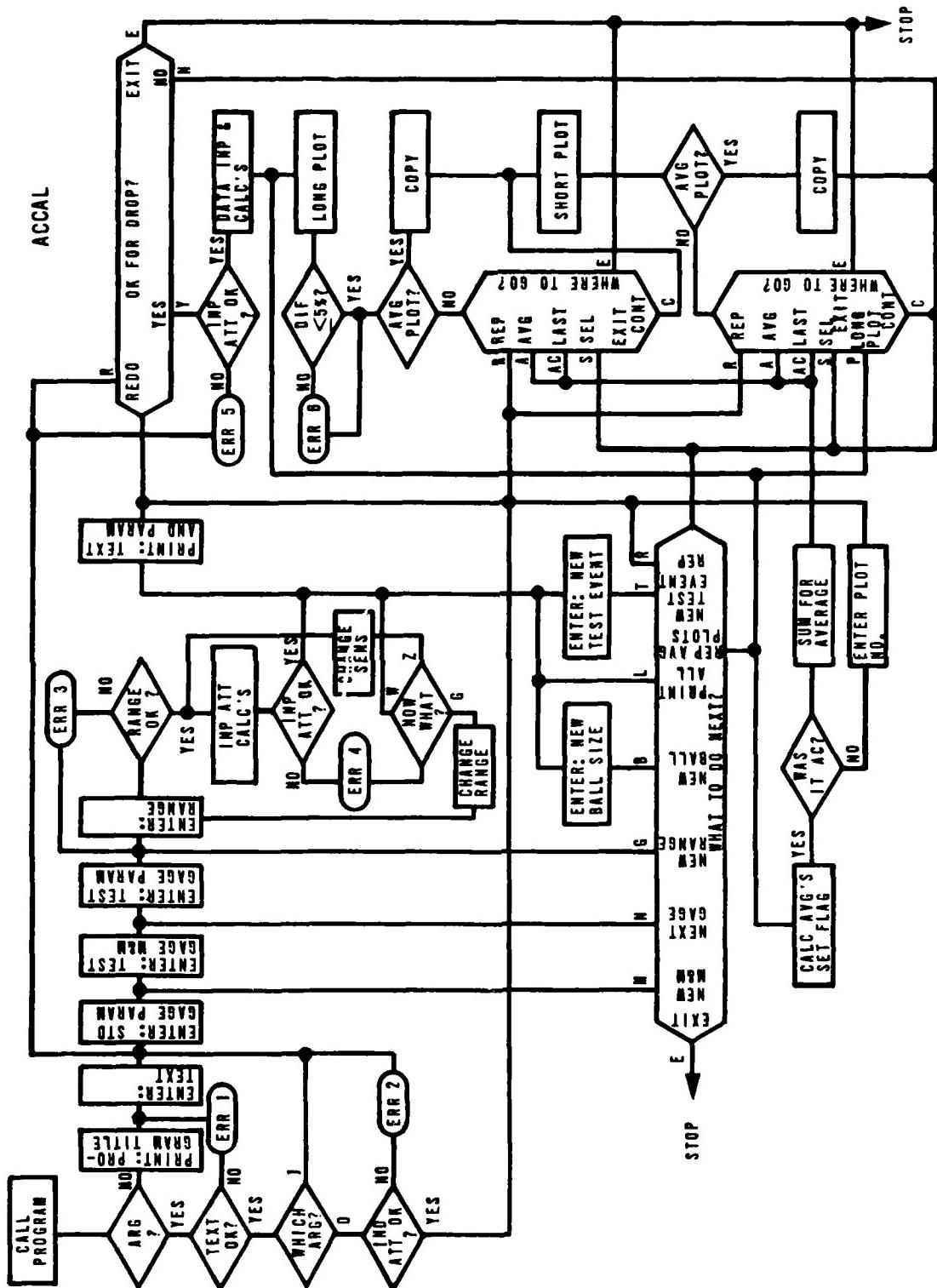
Figure 24. Decision diagram accelerometer calibration program.

TEST, DATE, AND NAME MISSING

TEST IN WHICH GAGE WILL BE USED:

Figure 25.   ERR1 message.

     e.   A 0 in the argument leads to a check to see if the gage parameters are properly set up (again they would not be if, e.g., this was the first call). The input attenuator code is a good criterion for that because it is calculated from range and gage sensitivities. If it does not have a proper value an error is printed (ERR2, Fig. 26), and the program loops back for reentering proper parameters.

     f.   If the input attenuator code is a proper one, the program goes to the OK FOR DROP? question. The regular program (no argument on the call) winds up at this same place, after it has performed the range selection and the input attenuator code calculation (para 3.3.3.4.2 and 3.3.3.4.3).

     g.   If the answer is NO, the SWITCH (list of action requests) is displayed for selection of further action. An EXIT request leaves the program and a REDO goes back to the parameter entry.

     h.   If the answer is YES, the input attenuator code is again interrogated (to find out whether the calculations in the INPMAX subroutine have yielded a proper one). If it is not correct, an error message (ERR5, Fig 27) is printed and the program goes back again to the parameter entry.

     i.   If the input attenuator code is correct, the program proceeds to arm the input and print a message (Fig. 15). When the trigger comes in, and while the two simultaneous inputs are taken, another message is printed (Fig. 17).

SETUP MISSING

STD GAGE S/N:

Figure 26.   ERR2 message.

```
TEST: HAVE HOST AT NTS, DABS I
DATE: 6 MARCH 1980   NAME: SCHNEIDER
TEST GAGE: ENDEVCO 2264A 2K ,S/N: 67890,MFR.SENS: 5.(MV/G)
           CALC.SENS: 0.(MV/G),PEAK: 0.(G),DIF: 0%

STD. GAGE: S/N: 12345,SENS: 1.96(MV/G),PEAK: 0.(G)

RANGE: 2500(G), GAIN: .5, ANVIL: 14889.1, BALL: 1.125

OK FOR DROP(Y OR N),OR REDO ALL(R),OR EXIT(E)? Y

NOT TRUE!!!



STD GAGE S/N:
```

Figure 27. ERR5 message.

j. The baseline is corrected next. Analog inputs have (from various sources) a slight offset that cannot be removed properly with a.c. coupling. Therefore, d.c. coupling is used and the offset calculated by averaging over the first 128 points of the data (this is an area where the data are kept at zero g by setting a delay in the calibrator between the trigger and the data). The entire block of data is then corected with this value.

k. Calibration in g's is performed and the peak value of each data block is found.

l. The measured sensitivity is derived from the measured peak values:

$$\text{Meas. Sens.} = \frac{\text{Peak (Test Gage)}}{\text{Peak (Std. Gage)}} \times \text{Entered Test Gage Sens.}$$

The difference between the measured sensitivity and the manufacturer's sensitivity is also calculated from the peak values:

$$\text{Difference} = \frac{\text{Peak (Std.)} - \text{Peak (Test)}}{\text{Peak (Std.)}} \times 100 \ (\%)$$

m. From the higher peak value, a common full-scale value for the plots is calculated.

n. Both inputs, the standard gage and the test gage, are displayed in the plot (see Fig. 18 for an example). After checking whether the calibration is more than ±5 percent off and sounding the tone four times when it is off (ERR6), the legend is printed on the plot. Two bells are always rung to advise the operator that a plot is available.

o. If the plot is not right, a direct repeat of the input can be requested, or a skip to the SWITCH for selecting an option, or one can exit, if desired. If averaging is wanted, the peak values are summed, and, after the last data are averaged, the average peak values and sensitivity are calculated. An automatic copy is made of both plots when the average is closed out with AC (Figs. 20 and 21).

p. If one cares to proceed, the short plot is displayed with the same legend (Fig. 19). The same options for leaving the plot are available in o. above, except for a chance to redisplay the long plot before going on.

q. On regular continuation, one winds up at the SWITCH (Fig. 22) from where one can do several things:

(1) Repeat without any changes in the setup,

(2) Enter a new g range,

(3) Enter the new S/N of the next test gage if it is the same model,

(4) Enter a new model and manufacturer of a test gage,

(5) Obtain a listing of the parameters and the text presently in force,

(6) Exit from the program (e.g., for a completely new start),

(7) Enter a new ball size. In this case a selection of ball sizes is printed from which one has be be chosen.

(8) Enter a new test event,

(9) Repeat the automatic plots. Subsequently, a new listing is displayed.

3.3.3.4.2 Subroutine RANGE (Fig. 28)

a. This routine serves to set up the fixed parameters based on the request range. A range chosen outside the limit of 50 to 10,000 g results in an error and a request to reenter (ERR3, Fig. 29).
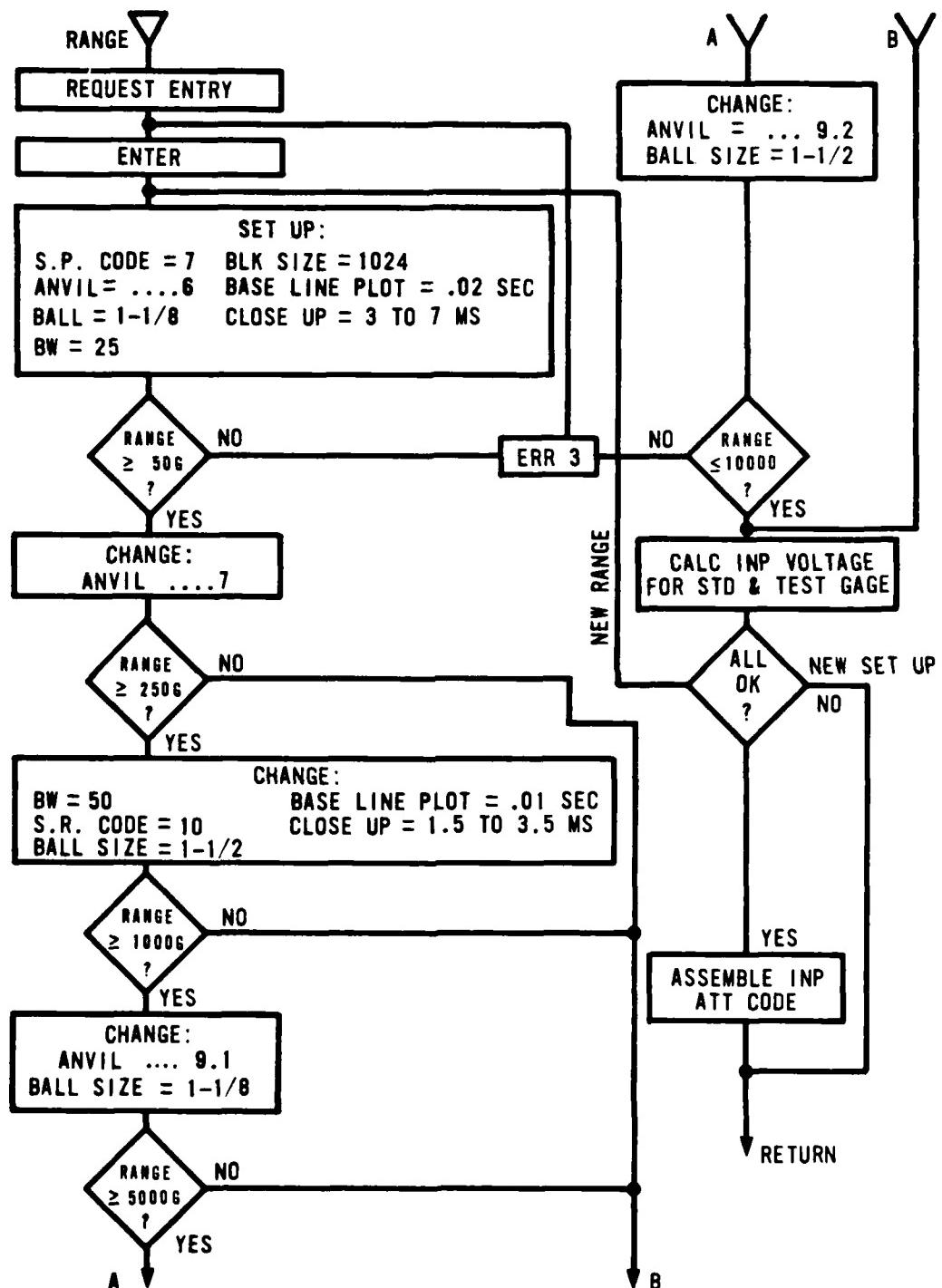
Figure 28.   Subroutine range.

SELECT RANGE BETWEEN 50 AND 10000 (G)

? 25
WRONG ENTRY, TRY AGAIN

?

Figure 29.   ERR3 message.

b.   The second purpose is to produce the input attenuator code from the calculations in the INPMAX subroutine.

c.   The options provided in INPMAX are exercised.

3.3.3.4.3 Subroutine INPMAX (Fig. 30)

a.   From the range and sensitivity as entered, the maximum expected input voltage is calculated. The input attenuator setting is started at half of the lowest full-scale available in the hardware.

b.   In a loop, the attenuator setting is increased by a factor of 2 until it is greater than the expected input voltage. Because the highest scale factor available in the hardware is 10, this setting has to be forced since it is not the next binary number.

c.   If the expected input voltage is still higher, this results in an error message (ERR4, Fig. 31) with an option

(1) to reenter a proper gage sensitivity.

(2) to request a new g range.

(3) to go back for a completely new setup.

3.3.3.4.4 Subroutine NAMIN (Fig. 32)

a.   The purpose of the routine is to accept characters from the keyboard one at a time and to enter them in a designated area in the text block.

b.   The entered character is echoed back to the screen (type-writer effect). The character is loaded when neither a Rubout nor a CTRL U had been encountered. The rubout allows the correction of a single wrong
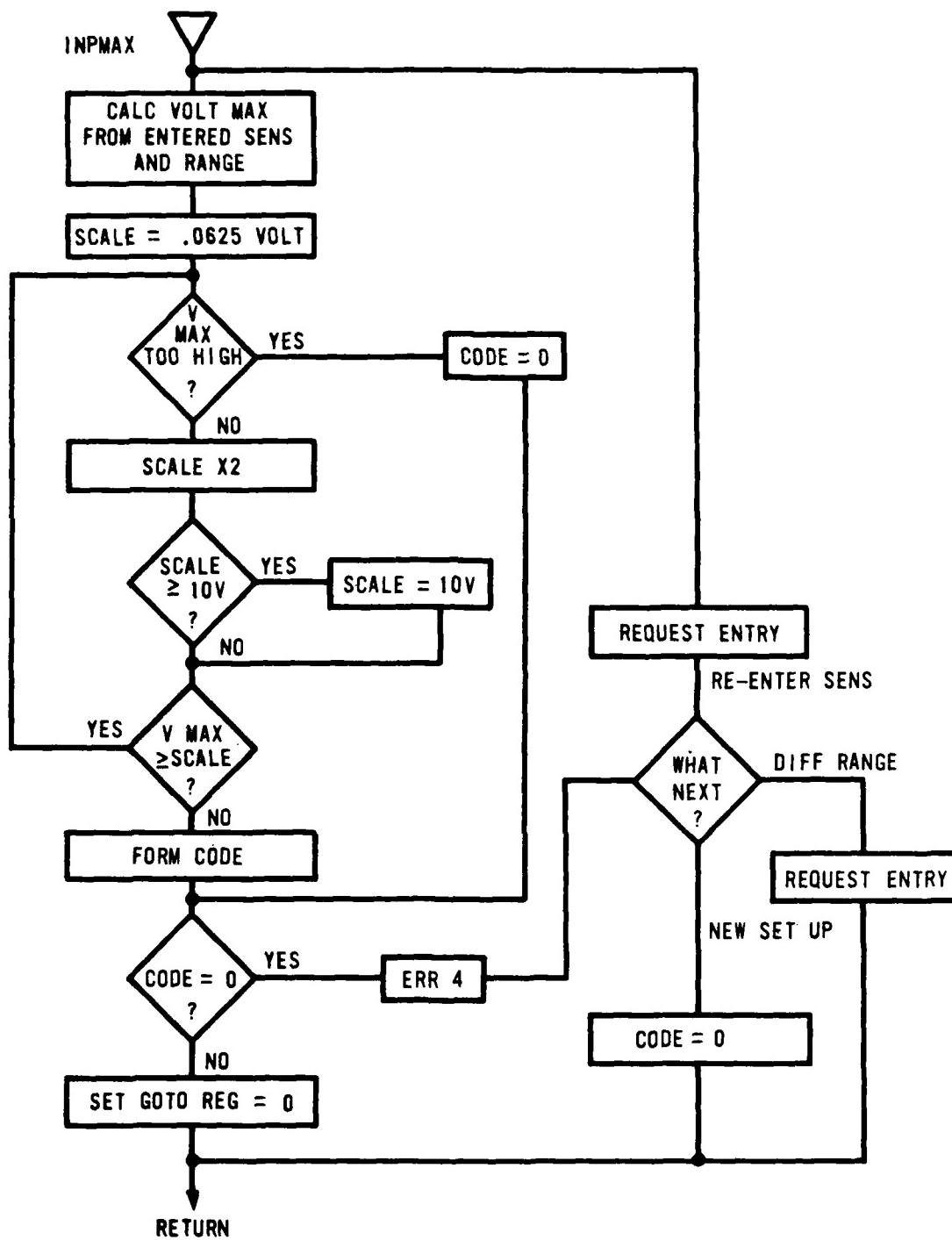
Figure 30. Subroutine INPMAX.

THIS IS THE ACCELEROMETER CALIBRATION PROGRAM

CONNECT REF TO 'A' AND TESTGAGE TO 'B' INPUT

TEST IN WHICH GAGE WILL BE USED:
HAVE HOST AT NTS, DABS I

DATE: 6 MARCH 1980
NAME: SCHNEIDER

STD GAGE S/N: 12345
STD GAGE SENS(MV/G):
? 1.96

TEST GAGE MAKE & MODEL: ENDEVCO 2264A 2K

TEST GAGE S/N: 67890
TEST GAGE SENS(MV/G):
? 2

SELECT RANGE BETWEEN 50 AND 10000 (G)

? 5000
TEST OUTPUT TOO HIGH
REENTER SENS(S),OR DIFF RANGE(R),OR WHOLE SETUP(C):


Figure 31.   ERR4 message.
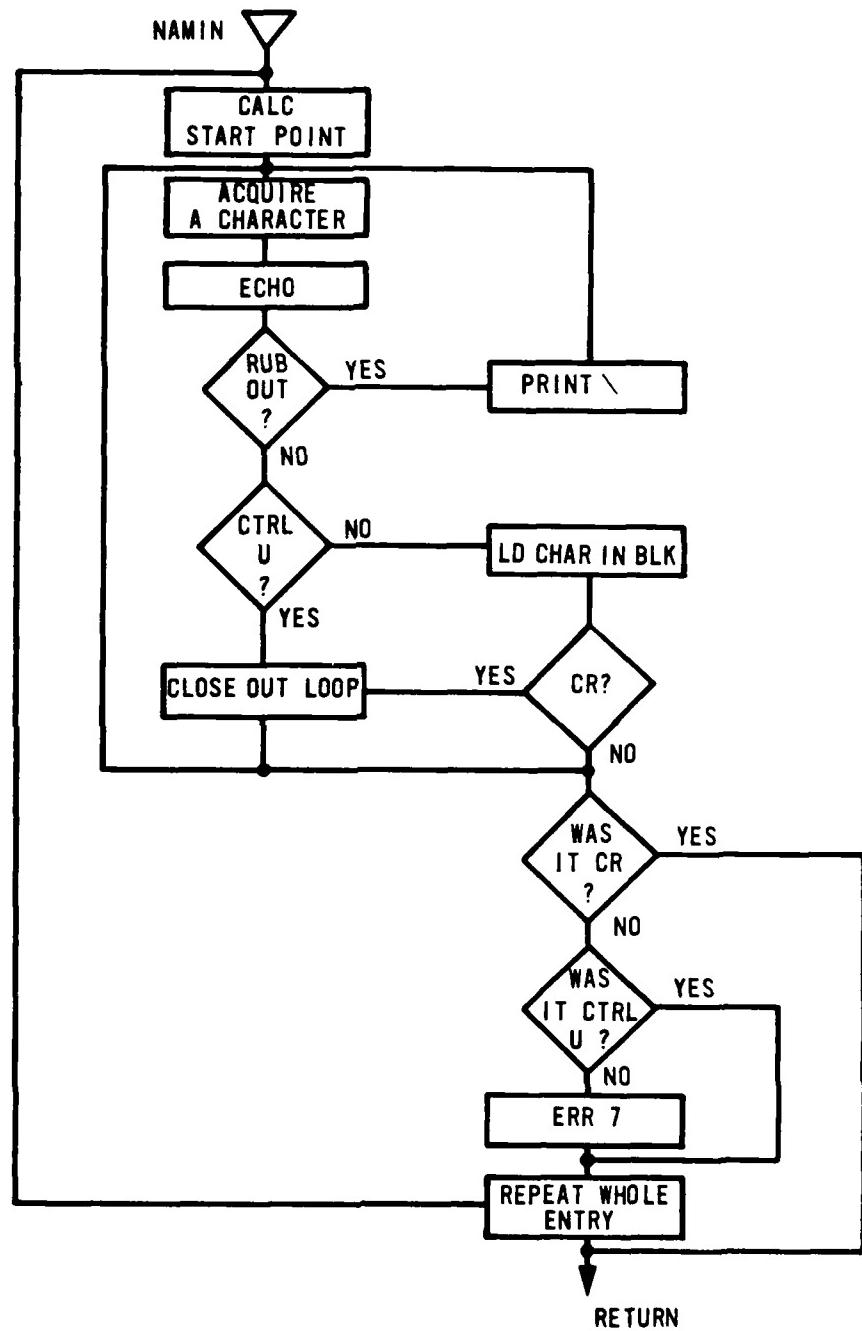
Figure 32. Subroutine NAMIN.

character on the spot. If more than one character is wrong, Ctrl U can be used to retype the entry. When a CR, or a CTRL U is encountered, the loop is closed out.

c. When the loop closes out and there is a CR typed, the routine goes to its end. If no CR is there, nor a CTRL U as the last character, the entry has obviously run over the limit. An error message ('ERR', fig. 33) is printed with the request to reenter. The routine returns to the start. A CTRL U will not print a message but just request to reenter, and the subroutine returns to the start.

THIS IS THE ACCELEROMETER CALIBRATION PROGRAM
CONNECT REF TO 'A' AND TESTGAGE TO 'B' INPUT
TEST EVENT IN WHICH GAGE WILL BE USED:
TRIPLE-SUPER-DUPER-FALLTHROU
TOO MANY CHAR'S! DO AGAIN:

Figure 33. ERR7 message.

3.3.3.4.5 Subroutine NAMOUT (Fig. 34)

a. The routine fetches a character one at a time from the selected text block area and prints it on the screen in the location pointed to by the cursor.

b. A CR can or may not be printed, depending on a code argument. If it is printed, an LF (line feed) is automatically attached.

c. A long text can be broken into several lines. If the last character of a line is a space, a CRLF is printed and the space is omitted. If it is not a space, a hyphen is printed, then a CRLF, and finally the character on the next line.

d. . . . . . Subroutine ADAT (fig. 35)

e. This routine determines whether . . . . the number if the first page of text printed out.
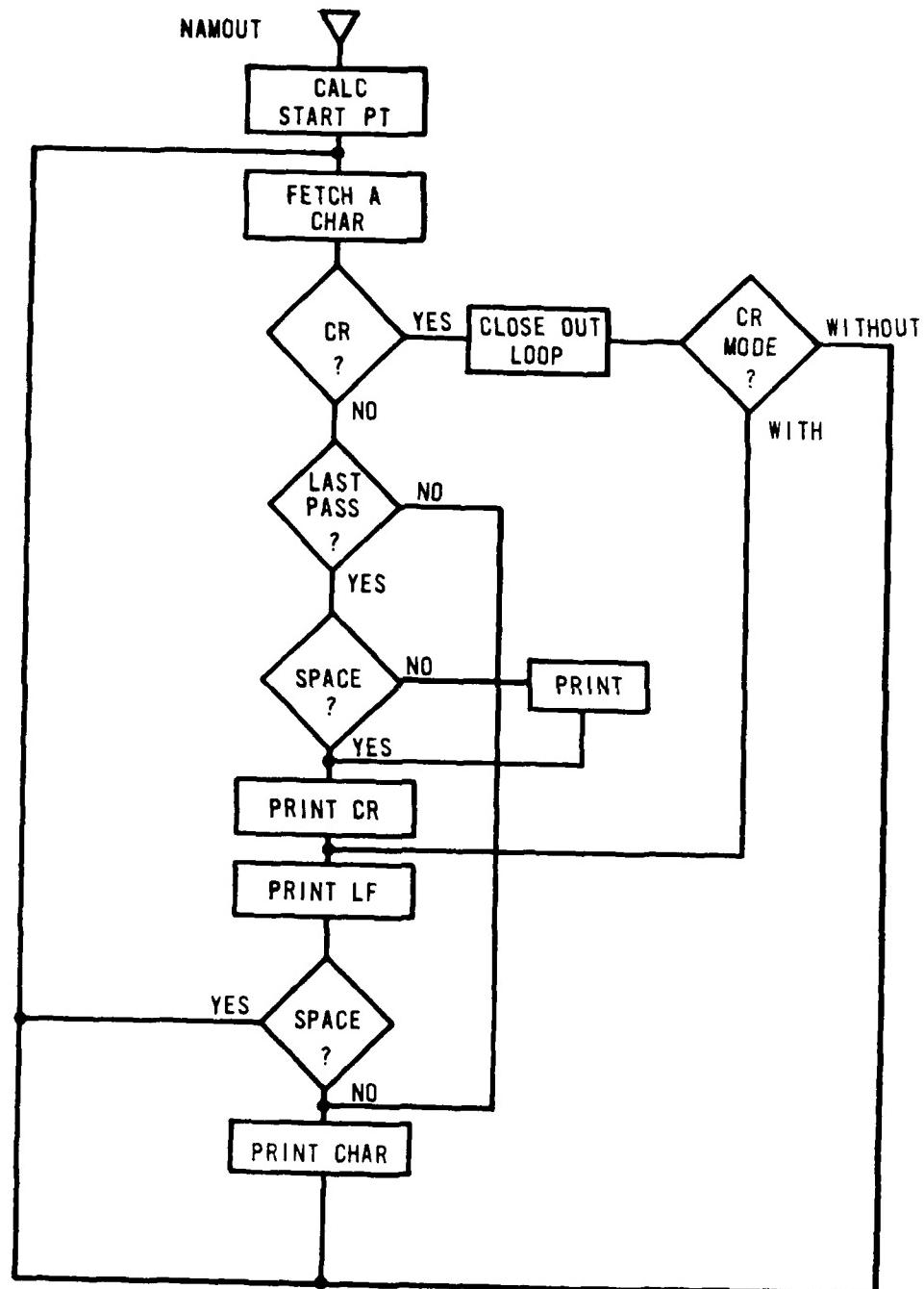
Figure 34.   Subroutine NAMOUT.
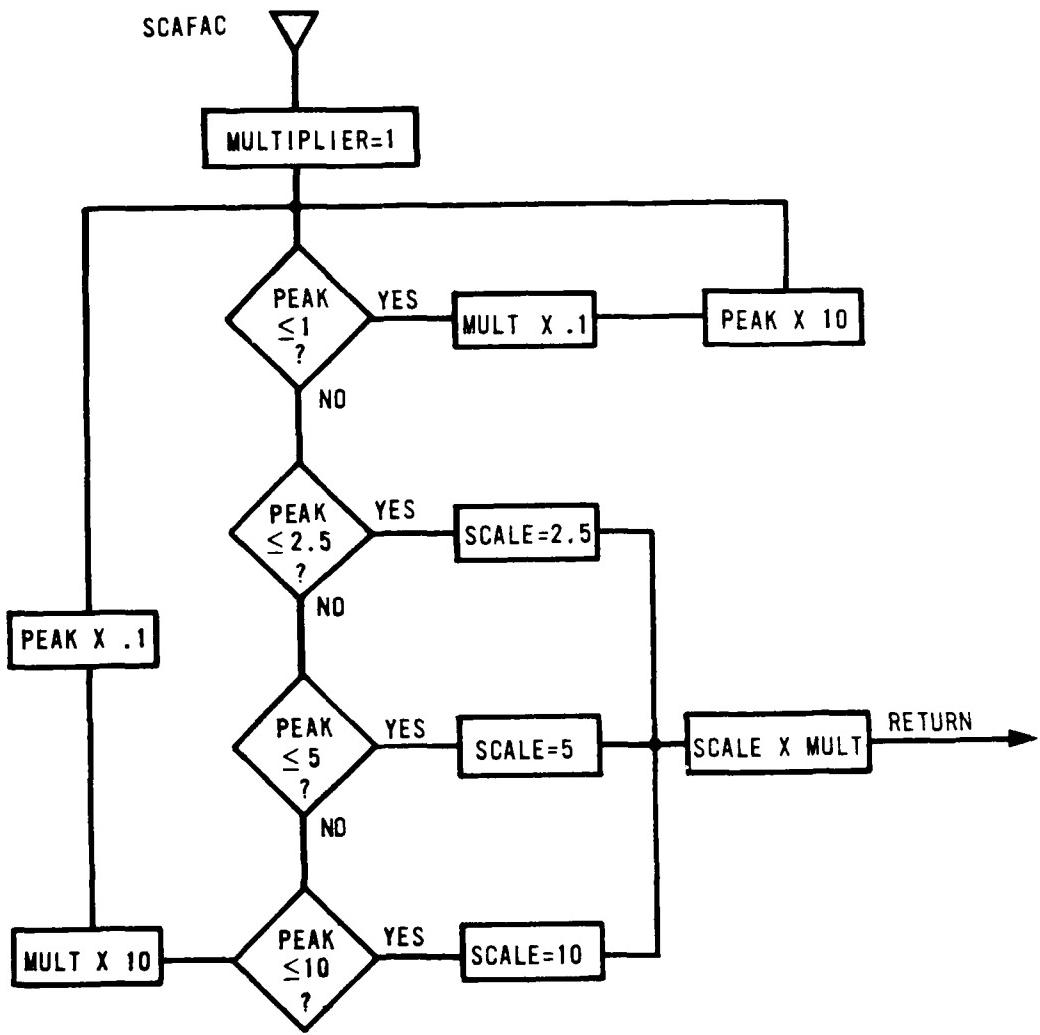
Figure 35. Subroutine SCAFAC.

b. In order to have a criterion for the order of magnitude, the signal peak is scaled up or down by factors of 10 while a multiplier keeps track of the powers of 10. Then a full-scale value of 1, 2.5, or 5 is determined. At the end of the routine, the multiplier restores the scale value to the previous power of 10.

3.3.4.7 Other Subroutines

a. All other TSL subroutines are not described because they are simple and can easily be understood from the source listings.

b. The binary routines are described in the TSL program package (Ref. 4) and are not needed for the understanding of ACCAL.

3.3.4 Accuracy. The step from taking measurements with a ruler from Polaroid scope pictures to using a calibrated instrument in the sense of a fast voltmeter, brings a great increase in accuracy of the measurement. Since it is difficult to assess the accuracy of the previous method, however, the increase cannot be expressed in a numerical factor.

The TSL equipment used for computer input has a 12-bit converter, that is an error of approximately ±0.05 percent. The input amplifiers are specified at ±3 percent with 0.1 percent linearity. The input filters add another ±1 percent absolute uncertainties. The excitation voltage can easily be set up to be within ±1 percent. The standard accelerometers are certified at ±2 percent accuracy by the standards lab. This includes the charge amplifier at its normally used gain setting.

The averaging of drops helps to decrease the statistical variations between measurements, e.g., averaging four drops reduces the statistical "noise" by a factor of 2 (Ref. 5). Because these accuracy statements are for maximum deviations, the errors should not simply be added algebraically but rather geometrically (Ref. 6). The absolute error is then (neglecting the contributions below 0.1%) $E = [(1\%)^2 + (2\%)^2 + (3\%)^2]^{1/2} = 3.7\%$. However, the drop ball calibration measurements are comparative rather than absolute as far as the measuring equipment is concerned. Then only the registration differences between the two measurement channels are important. These have been determined to be less than ±1 percent on all settings of the input attenuator and the filters that are used for the calibration measurements.

Therefore, with the measurement system providing a maximum of ±1 percent uncertainties, the accelerometer calibration accuracy can be derived from the 2 percent of the standard accelerometer and the 1 percent of the system setup, which amounts to a total of ±2.25 percent. The repeatability of the measurements is better than ±1 percent.

Compared to the figures in Ref. 1, which have been calculated for the manual scope display, and which are used here just to give an idea of the proportion, the automated procedure has gained calibration accuracy improvement by more than a factor of 2 for the whole process.

IV. EQUIPMENT

4.1 ANALOG ELECTRONIC HARDWARE

The meters to monitor current, resistances, and voltages should be 3-1/2
to 4-1/2 digit digital multimeters. The megohm meter should allow measure-
ments to 100 MΩ. The low-pass filters in the signal lines to the computer
should be able to provide a linear phase low-pass characteristic with at least
24 dB/octave slope in the 0.5-kHz to 10-kHz bandwidth range. An important
part of this equipment is the "signal conditioner" which was built in-house to
perform the required measurements. Besides the gage excitation adjustment and
balance trim, the signal conditioner has a function switch that allows making
the static measurements (para 3.2.3) without having to change test leads.

4.2 DIGITAL ELECTRONIC HARDWARE

Since the software is working within the TSL programming system that has
the analog-to-digital interface control instructions, it is necessary to use
the TSL computer front end which contains the triggering circuit, the input
attenuator, antialiasing filters, the sample rate and number of samples selec-
tors, and the analog-to-digital converter. This front-end system connects to
the Unibus* of practically any PDP-11 computer that can run the RT-11 oper-
ating system. A minimum of 28K of random access memory (RAM) is necessary,
also the extended arithmetic functions have to be available. A CRT terminal
needs to have bit addressing for the graphics of the plots, and the bit has to
be connected to a hard-copy machine for obtaining the printed documents of the
results.

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* trademark of Digital Equipment Corporation, Maynard, MA.

V. CONCLUSION

A viable and useful calibration system has been designed and implemented. Numerous calibrations have been performed since the two years the system has been in operation. The time required to do the drop ball part of the gage calibration has been decreased by a factor of 10 by automating the procedure.

Improvements have been made since, especially in the software. Of particular interest might be a sister program package that allows cross-axis sensitivity testing.

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